

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
27 November 2008 (27.11.2008)

PCT

(10) International Publication Number
WO 2008/144337 A1

(51) International Patent Classification:
H01L 33/00 (2006.01)

(21) International Application Number:
PCT/US2008/063597

(22) International Filing Date: 14 May 2008 (14.05.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/938,209 16 May 2007 (16.05.2007) US

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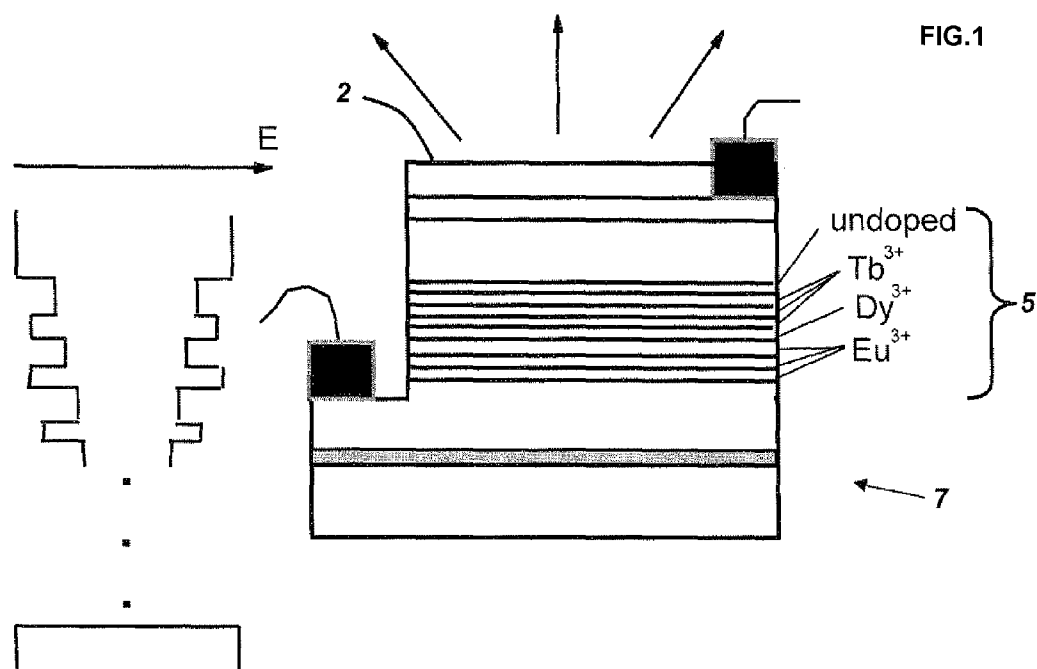
(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

(54) Title: LIGHT EMITTING DIODE BASED ON MULTIPLE DOUBLE-HETEROSTRUCTURES (QUANTUM WELLS) WITH RARE EARTH DOPED ACTIVE REGIONS



(57) Abstract: A light-emitting diode having a light-emitting surface is described. The light-emitting diode comprises a series of quantum well layers wherein one or more of the quantum well layers is doped with one or more activator ions that emit light and the quantum well layers are arranged in a sequence whereby the light emission from a lower quantum well layer is not significantly absorbed by quantum well layers between the lower quantum well layer and the light-emitting surface.

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LIGHT EMITTING DIODE BASED ON MULTIPLE DOUBLE-HETEROSTRUCTURES (QUANTUM WELLS) WITH RARE EARTH DOPED ACTIVE REGIONS

Cross Reference to Related Application

[0001] This application claims the benefit of U.S. Provisional Application No. 60/938,209, filed 5/16/2007.

Technical Field

[0002] This invention pertains to solid state light sources based on GaN-AlGaIn-InGaIn alloys with rare earth doping. Gallium, aluminum and indium nitride alloys with terbium, europium and/or other rare earth ions have been previously proposed as active layers for phosphorless white light emitting double heterostructure (DHS) LEDs (See, US Patent Publication No. 2005/0253162).

Background of the Invention

[0003] Luminescence from various activator ions doped into a nitride semiconductor alloy is based on energy transfer from host material (the alloy) to the activator ion (the rare earth). The efficiency of this energy transfer depends on several factors including the band gap (BG) energies of the host or band gap emission (BGE). It is possible to optimize the electronic structure and BGE energy of the host for one particular type of dopant ion by changing the alloy composition so that the luminescence efficiency of this host-activator combination is at its maximum. However, for generating better quality white light, more than one activator type for multiple color components is needed. It may be difficult to achieve optimum conditions for the energy transfer to multiple activators. It may prove equally hard to simultaneously incorporate notable concentrations of various activator ions in the same lattice for efficacious white light emission.

Summary of the invention

[0004] It is an object of the invention to obviate the disadvantages of the prior art.

[0005] It is another object of the invention to provide a light-emitting diode having a novel multiple quantum well structure.

[0006] It is a further object of the invention to provide a white-light-emitting diode.

[0007] In accordance with these and other objects and advantages, there is provided a light-emitting diode having a light-emitting surface, the light-emitting diode comprising a plurality of quantum well layers wherein one or more of the quantum well layers is doped with one or more activator ions that emit light and the quantum well layers are arranged in a sequence whereby the light emission from a lower quantum well layer is not significantly absorbed by quantum well layers between the lower quantum well layer and the light emitting surface. Preferably, the quantum well layers are arranged in a sequence of increasing band gap energy and comprise an AlGaInN alloy.

[0008] In another aspect of the invention, the light-emitting diode includes a stack of quantum well layers comprising a first quantum well layer that emits a red light and is doped with Eu^{3+} , a second quantum well layer that emits a yellow light and is doped with Dy^{3+} , a third quantum well layer that emits a green light and is doped with Tb^{3+} , and a fourth quantum well layer that emits a blue light, the quantum well layers being arranged in order according to their emission wavelength wherein the first quantum well layer is furthest from the light-emitting surface.

Brief Description of the Drawing

[0009] The Figure is illustrates a AlGaIn-based multiple quantum well (MQW) structure with a combination of active regions emitting in red (Eu^{3+}), yellow (Dy^{3+}), green (Tb^{3+}), and blue (undoped) spectral regions.

Detailed Description of the Invention

[0010] Generation of white light with a desired correlated color temperature (CCT) and color rendering index (CRI) is achievable in devices having multiple active layers (or thin quantum wells, QWs). Each layer is based on an alloy composition optimized

for a particular host-activator combination which produces the desired color with maximum quantum efficiency. Such layers are stacked according to their emission wavelengths and the number and thickness of layers from each type is determined by the overall optimum conditions for desired optical and electrical performance.

[0011] Active layers of DHSs (or quantum wells) in nitride-based LEDs doped with the rare earth ions of more than one type (for example, trivalent Tm+Tb+Eu or Dy+Eu, to name only two combinations) are expected to emit light that is perceived as white due to simultaneous luminescence from the host and dopants in various parts of the visible spectrum. Instead of relaxing across the BG as in pure semiconductors, the recombination of injected electrons and holes may involve the dopant ion with a probability determined by a number of factors. White light is formed with or without a significant contribution due to the host alloy itself (BGE, typically in the blue spectral range), depending on the choice and concentration of these activator ions. Each rare earth ion (in this case Pr, Eu, Tb, Dy, Er or Tm in a +3 state) exhibits multiple emission lines across the visible spectrum arising from 4f-4f electronic transitions. These transitions change very little from host to host and due to one or two dominant transitions generate a light of a particular color characteristic to that ion (e.g. red for Eu^{3+} , green for Tb^{3+} or Er^{3+}). At the same time, the transitions involving excited states of the outer orbitals of the rare earth (such as 5d) or host ions (as in charge transfer) may shift significantly in energy with various cation-ligand combinations of the lattice. This affects strongly the luminescence efficiency of each ion in that lattice.

[0012] The energy transfer from the host lattice to the dopant ion may proceed via more than one mechanism with the effectiveness of each channel depending on several factors. Some of them, like the position of host energy levels, the size of the BG and hence also the BGE energy relative to the positioning of ground and excited states of the dopant can be modified by varying the host alloy composition. This allows for the optimization of dopant luminescence efficiency in nitride alloys via changes in cation composition, for example by tuning the Ga/In ratio in $\text{In}_x\text{Ga}_{1-x}\text{N}$. However, it is unlikely

that rare earth ions emitting through very different excitation mechanisms (cf. Eu^{3+} and Tb^{3+}) will achieve optimum efficiencies for the same alloy composition.

[0013] A DHS consists of an active layer sandwiched between the two cladding layers that confine the charge carriers to the recombination region due to a larger band gap (an alloy with different cation composition and no rare earth doping) than that of the active region. Band discontinuities much larger than kT help in concentrating the electrons and holes for effective recombination (quantum efficiency). The thickness of the active layer in a typical DHS is application optimized and ranges from $\sim 100\text{nm}$ to $\sim 1000\text{nm}$ while in a QW it is of several nanometers. QWs are typically used in multiples (MQWs). For the latter, the confinement layers control the flow of carriers between the adjacent wells. Their height and thickness, in turn, are dictated by achieving efficient, homogeneous charge carrier distribution. Higher barriers may be used for overall confinement of electrons and holes in the MQW region. Coupling or stacking the DHSs follows the same general rationale but since providing homogeneous current distribution and extracting of the light becomes increasingly difficult for thick layers, we describe the structure from here on as consisting of QWs.

[0014] In present case, each single QW would constitute a combination of the dopant rare earth ion and $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$ alloy with an optimized composition (x,y) to produce maximum desired luminescence efficiency of the desired color (or color combination with alloy emission).

[0015] As shown in the Figure, the QWs 5 in the LED 7 are stacked in the sequence of increasing band gap and emission energy so that the red emission (Eu^{3+}) from the lowest QW in the stack is furthest from the topmost, light-emitting surface 2. (See, energy diagram to left of LED 7). This way, the re-absorption of light by the host alloys is largely avoided. The choice of activators and their concentrations, number of QWs of each type as well as all other parameters will be determined corresponding to the application and considering the maximum possible efficacy. In a preferred embodiment, the AlGaIn -based MQW structure is constructed with active regions emitting in red

(Eu³⁺), yellow (Dy³⁺), green (Tb³⁺), and blue (undoped) spectral regions and are stacked in order according to their emission wavelength with the red-emitting layer being furthest from the LED's light-emitting surface.

[0016] While there have been shown and described what are at present considered to be preferred embodiments of the invention, it will be apparent to those skilled in the art that various changes and modifications can be made herein without departing from the scope of the invention as defined by the appended claims.

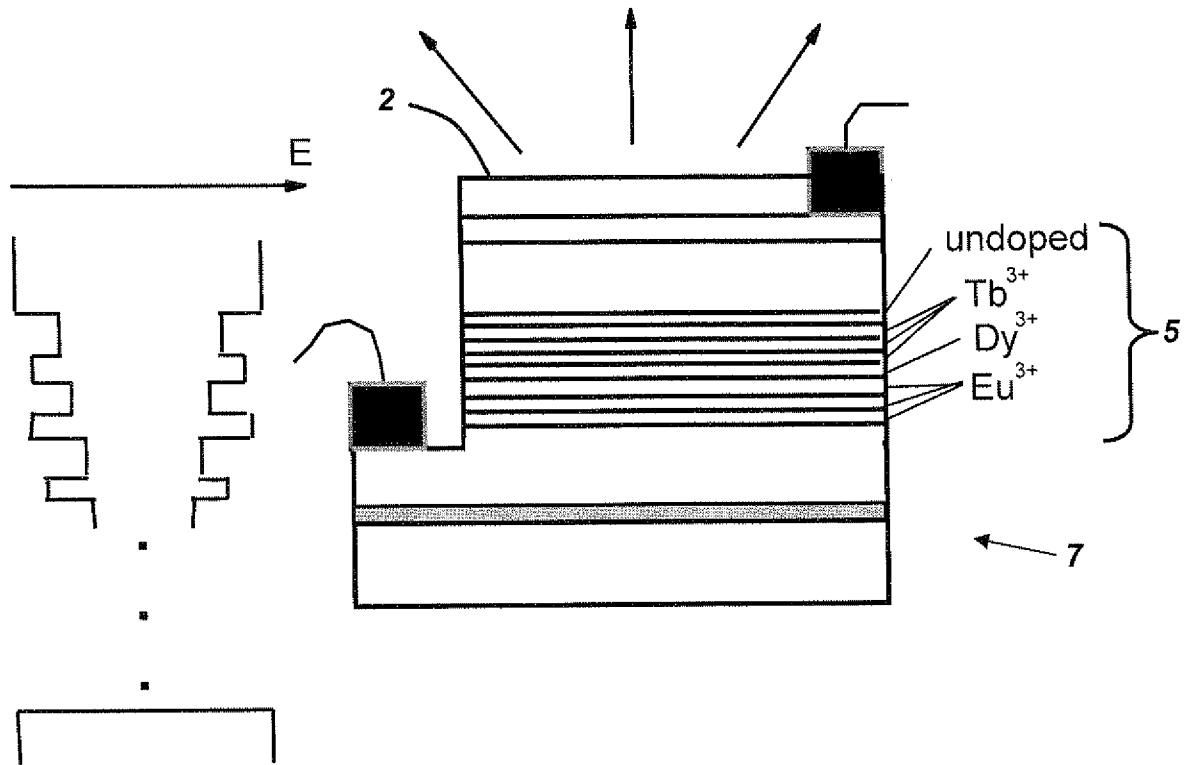
Claims:

We claim:

1. A light-emitting diode having a light-emitting surface, the light-emitting diode comprising a plurality of quantum well layers wherein one or more of the quantum well layers is doped with one or more activator ions that emit light and the quantum well layers are arranged in a sequence whereby the light emission from a lower quantum well layer is not significantly absorbed by quantum well layers between the lower quantum well layer and the light emitting surface.
2. The light-emitting diode of claim 1 wherein the quantum well layers are arranged in a sequence of increasing band gap energy.
3. The light-emitting diode of claim 1 wherein the quantum well layers are comprised of an AlGaInN alloy.
4. The light-emitting diode of claim 1 wherein each quantum well layer that is doped with an activator ion contains a different type of activator ion than the other quantum well layer(s) that are doped with activator ion(s).
5. The light-emitting diode of claim 1 wherein the quantum well layers comprise at least one red-emitting, one yellow-emitting, one green-emitting and one blue-emitting quantum layer.
6. The light-emitting diode of claim 5 wherein the red-, yellow-, green- and blue-emitting quantum wells are stacked in order according to their emission wavelength with the red-emitting quantum layer being furthest from the light-emitting surface.
7. A light-emitting diode having a light-emitting surface, the light-emitting diode including a stack of quantum well layers comprising a first quantum well layer that emits

a red light and is doped with Eu^{3+} , a second quantum well layer that emits a yellow light and is doped with Dy^{3+} , a third quantum well layer that emits a green light and is doped with Tb^{3+} , and a fourth quantum well layer that emits a blue light, the quantum well layers being arranged in order according to their emission wavelength wherein the first quantum well layer is furthest from the light-emitting surface.

8. The light-emitting diode of claim 7 wherein the quantum well layers are comprised of an AlGaInN alloy.



INTERNATIONAL SEARCH REPORT

International application No

PCT/US2008/063597

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	YAMADA M ET AL: "PHOSPHOR FREE HIGH-LUMINOUS-EFFICIENCY WHITE LIGHT-EMITTING DIODES COMPOSED OF INGAN MULTI-QUANTUM WELL" JAPANESE JOURNAL OF APPLIED PHYSICS, JAPAN SOCIETY OF APPLIED PHYSICS, TOKYO.; JP, vol. 41, no. 3A, PART 02, 1 March 2002 (2002-03-01), pages L246-L248, XP001186615 ISSN: 0021-4922 page L246, column 1, line 25 - column 2, line 11; figure 1 page L247, column 2, line 8 - page L248, column 2, line 5; figure 6 page L248, column 2, lines 11-17; figure 3 ----- -/--	1-8



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

A document defining the general state of the art which is not considered to be of particular relevance

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L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

Z document member of the same patent family

Date of the actual completion of the international search

16 September 2008

Date of mailing of the international search report

24/09/2008

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2008/063597

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2000 091703 A (SONY CORP) 31 March 2000 (2000-03-31) abstract paragraphs [0001] - [0004], [0006] - [0008], [0013] - [0018], [0020] paragraphs [0028] - [0030]; figure 2 paragraphs [0038], [0043]; figure 1	1-8
X	WO 2007/021017 A (NGK INSULATORS LTD [JP]; COMMISSARIAT ENERGIE ATOMIQUE [FR]; HORI YUJI) 22 February 2007 (2007-02-22) page 1, lines 5-15 page 7, line 23 - page 8, line 5 page 12, line 8 - page 13, line 15; figure 1 page 14, lines 17-20 page 24, line 14 - page 25, line 2 page 25, lines 13-15	7,8
A	US 2005/206312 A1 (CHO JAE-HEE [KR]) 22 September 2005 (2005-09-22) paragraphs [0003], [0009] - [0011], [0017] - [0022]; figures 1,2 paragraphs [0024], [0025]; claims 1,3,4	
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2008/063597

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